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REVIEWS AND ANALYSES

Managing Nitrogen for Water Quality—Lessons from Management Systems Evaluation Area

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ABSTRACT

The Management Systems Evaluation Area (MSEA) project was initiated in 1990 to evaluate existing and develop new N management technologies to reduce the potential adverse impacts of agricultural practices on surface and ground water quality. Field research sites were established in nine Midwestern states. Results from MSEA research showed that nitrate leaching was greatly reduced by changing from furrow to sprinkler irrigation. At least 95% of the nitrate N percolating through tiled soils was intercepted and discharged into surface waters. Computer models indicated that routing tile discharge through wetlands would greatly reduce the nitrate load. Nitrate losses also were reduced by establishing controlled water tables using drainage lines for subirrigation. Preplant and presidedress soil nitrate tests were effective in determining proper N fertilizer rates and reducing nitrate losses. Banding ammoniated fertilizers slowed nitrification rates and nitrate leaching, especially if soil over the bands was packed. A major new technology was proof that crop greenness can be used to monitor crop N sufficiency, and that N deficiencies after the V8 stage can be corrected by sidedressing or fertigation (reactive N management). Inexpensive sensors or aerial photographs can be used to assess crop greenness. Using Global Positioning Systems (GPS), N–deficient areas of the field can be managed differently from the remainder of the field. These results point to the need to develop site-specific or precision farming systems to control nitrate losses to water resources and reduce the impact of natural variability in both soils and weather.

THE MSEA projects discussed in this paper were initiated in response to the 1989 Presidential Water Quality Initiative, enacted by the U.S. Congress. The initiative was led by the U.S. Department of Agriculture to assess capabilities of present crop production technology and to develop improved technologies to control nitrate leaching from soils. The MSEA project, initiated in 1990, focused on the Corn Belt of the USA, with supplemental research on specific topics conducted at other locations. The primary goals of the MSEA program were to: (i) evaluate the distribution of agricultural chemicals in water resources and identify the factors that affect distribution, and (ii) develop new, improved, and acceptable agricultural management systems that enhance water quality (Onstad et al., 1991).

Five major sites were funded by USDA for five years to conduct research to evaluate the effectiveness of existing technologies and to develop new technologies that would lessen the nitrate pollution problem. The major sites were located in Ohio, Minnesota, Iowa, Missouri, and Nebraska (Fig. 1). At some locations satellite sites were also established to provide wider coverage, including sites in Kansas, North Dakota, South Dakota, and Wisconsin. This was the largest research and education effort ever organized in the USA to study this problem, led by the Agricultural Research Service and Cooperative Research, Extension, and Education Service of the U.S. Department of Agriculture. The MSEA project was cooperative with State Agricultural Experiment Stations in these states, as well as the USDA Federal

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Abbreviations: MSEA, Management Systems Evaluation Area; GPS, Global Positioning Systems; PPNT, preplant nitrogen test; PSNT, presidedress nitrogen test; GLEAMS, Ground water Loading Effects of Agricultural Management Systems; RZWQM, Root Zone Water Quality Model; NLEAP, Nitrate Leaching and Economic Analysis Package; SWAT, Soil and Water Assessment Tool.

Fig. 1. Location of MSEA research sites.

Extension Service and Natural Resources Conservation Service, the U.S. Geological Service, and the Environmental Protection Agency. Various other state and local agencies participated at many sites.

The purpose of this paper is to review the results of the N management research associated with the MSEA projects, which officially terminated in 1996. We discuss the capabilities of existing technology and the development of new technologies and practices for agricultural N management that resulted from these projects, and point out the direction of future research needed to follow up on this new information.

Managing fertilizer N inputs is a major factor in managing soil N availability and N losses to water resources. However, for the first 60 to 70 yr of the 20th century, we had no reliable soil tests to guide us in N fertilizer management (Nelson, 1987). About the only useful test for N availability was soil organic matter content. However, correlation coefficients between this parameter and N fertilizer response were usually only 0.5 to 0.7, suggesting only 25 to 50% accuracy in predicting soil N availability. This lack of a reliable soil test for soil N availability left agronomists with a challenge (Dahnke and Vasey, 1973; Meisinger, 1984; Keeney and Bremmer, 1996). Fortunately, within recent decades, major improvements in soil testing for N availability have been made.

About 35 yr ago, Professor Robert Olson and others at Nebraska (Olson et al., 1964) developed useable correlations between soil nitrate content to the 90 cm depth and crop response to N fertilization when soil samples were collected in the late fall or before planting in the spring. In higher rainfall regions, this approach had limited value because much nitrate leaching usually occurred during winter and spring months. In more recent years, Magdoff et al. (1984) and others found that workable correlations could be developed in humid climates if soils for nitrate analysis were sampled to the 30 to 60 cm within a few weeks before corn (*Zea mays* L.) planting (preplant nitrogen test—PPNT). Also, it was found that if only part of the N fertilizer requirement was applied at planting, the amount of additional fertilizer required later as a sidedressing could be predicted with reasonable accuracy from nitrate analysis of soil samples collected to the 60 to 90 cm depth before sidedressing (presidedress nitrogen test—PSNT). In later years the PPNT and PSNT techniques have been modified and calibrated to fit conditions prevailing in most Midwestern states, and now are used widely.

A major difficulty with the soil testing approach is that one must predict with acceptable accuracy both growing season weather and final crop yield at the time of applying the fertilizer. Historical records show great variation in both weather and crop yields from season to season, making prediction of either of them several months in advance unreliable. Because soil water is such an integral key in regulating soil microbial activity and subsequent N transformations and availability (Linn and Doran, 1984), inability to predict rainfall accurately during the coming crop season limits utility of soil N tests made prior to or shortly after planting. Because of this variability in weather between years and also variability of soils within a field, nitrate leaching still frequently occurs even when we use the best technology available. Kranz and Kanwar (1995) estimate that at least 70% of the nitrate N leached typically comes from less than 30% of a field. This problem will become more acute in future decades as increased world population will require greater crop yields, and presumably use of more added N in crop production enterprises. Thus, the need for additional research to address this problem is recognized.

ESTABLISHMENT OF MSEA PROJECTS

The MSEA project was conducted in the Midwestern USA because of the frequency of water quality problems in that region (Madison and Bennett, 1985). About

80% of the corn and soybeans [*Glycine max* (L.) Merr.] produced in the USA are grown in the Midwest, and over 50% of the fertilizer N used in the nation is applied in that region. Thus, the decision was made to focus this research project on the corn- and soybean-producing regions of the Midwest. However, some funding was also provided for additional research on specific topics or unique situations in other states.

The locations selected for the MSEA field research sites provide considerable diversity in conditions (Ward et al., 1994). The site in Ohio is characterized as being an alluvial river valley with a relative high water table in a humid climate. The Minnesota site was on a sandy outwash plain. Other sandy soil-shallow aquifer situations were studied in Wisconsin, North Dakota, and South Dakota. In Iowa sites selected included a tiled glacial till watershed, a tiled small plot research site, and field scale studies of nitrate leaching in deep loess soils. In Missouri the research concentrated on the fate of fertilizer N on clay-pan soils and watersheds. Research in Nebraska, and related research in Kansas, studied water and nitrate movement on irrigated alluvial soils. Collectively, these sites represented a good cross section of the soils on which crops are produced in the Corn Belt, especially those soils where a nitrate pollution problem is most likely to develop. Corn was the primary crop studied at all locations, grown both as continuous corn and in rotation with soybeans. In most instances, currently used production practices were compared with practices designed to improve the efficiency of use and conservation of N and water. Emphasis was placed on the impacts of these practices on crop yields and water quality. Frequently the effects of crop rotations, tillage practices, animal manures, and other such agricultural production practices were also evaluated. Most field studies were conducted 1991 through 1995. Observation wells were used at all sites to monitor the effects of the practices studied on water quality. Several lysimeter studies were also conducted. It is recognized that for many hydrological situations, there is little likelihood of observing significant effects on ground water quality within five years, when practices are modified.

RESULTS—LESSONS LEARNED FROM MSEA

Results obtained from MSEA research both verified information obtained from earlier research and provided knowledge on which to build new N management strategies. A number of these research results related to factors involved in N management are discussed in the following pages.

Water Management Practices Affecting Water Quality

The effects of a number of water management practices on nitrate movement and water quality were investigated at the different MSEA sites. These included irrigation practices, tile drainage, water table controls, terracing, and use of wetlands. Much of the irrigation research was conducted to evaluate the effects of con-

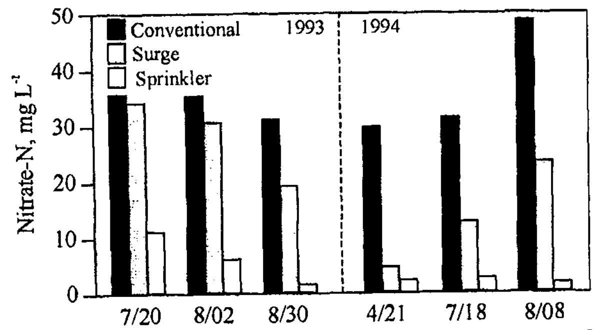

Fig. 2. Nitrate N concentrations in root zone drainage water at the Nebraska site under conventional, surge (modified furrow), and center pivot sprinkler irrigation (Watts and Schepers, 1995).

ventional furrow, improved furrow (surge), and sprinkler irrigation on water use, nitrate leaching, N recovery by crops, and crop yield. Compared with conventional furrow irrigation, use of a center-pivot sprinkler in Nebraska reduced annual water application rate from 100 to 140 cm to about 25 to 40 cm, and provided much better water control while maintaining or improving crop yields (Watts and Schepers, 1995; Watts et al., 1998). As a consequence, nitrate movement below the root zone was likewise greatly reduced (Fig. 2). Effects of surge irrigation were intermediate between these other two treatments. Other irrigation research showed that nitrate leaching could be reduced for furrow irrigation by running irrigation water through every other furrow, rather than every furrow, and applying the N fertilizer in the nonirrigated furrow (Martin et al., 1995). Generally, any furrow irrigation technique studied failed to provide uniform depth of water and nitrate movement over the entire field.

Approximately a third of the crop land in the Midwestern states of the USA is tile drained. Typically, tile drains are placed at least 1 m deep, with spacing between tile lines dictated by the permeability of the soil. Discharge from these tile lines is normally emptied into a surface water body, usually a drain ditch or natural stream. A well-designed tile drain intercepts at least 95% of the percolating water and nitrates and diverts most of this water through the tile line to the surface water body, carrying with it any nitrates dissolved in the percolating water (Hatfield et al., 1998). Thus, use of tile drainage converts potential ground water quality problems into potential surface water quality problems. The MSEA research results from Iowa showed that in some instances the equivalent of more than 100% of the fertilizer N applied could be accounted for in tile drainage discharge (Table 1). Thus, on a watershed ba-

Table 1. Loss of nitrate expressed as a fraction of that applied per subbasin for 1992–1994 (Jaynes et al., 1999).

	Subbasin no.						
Year	110	210	220	230	310	320	330
	Nitrate N loss (%)						
1992	0.15	0.12†	0.26	0.21†	0.37	0.40	0.40
1993	0.29	0.70	0.57	1.19	0.91	1.02	1.15
1994	0.03	0.10	0.04	0.06	0.08	0.07	0.06

† Flow not monitored for entire year.

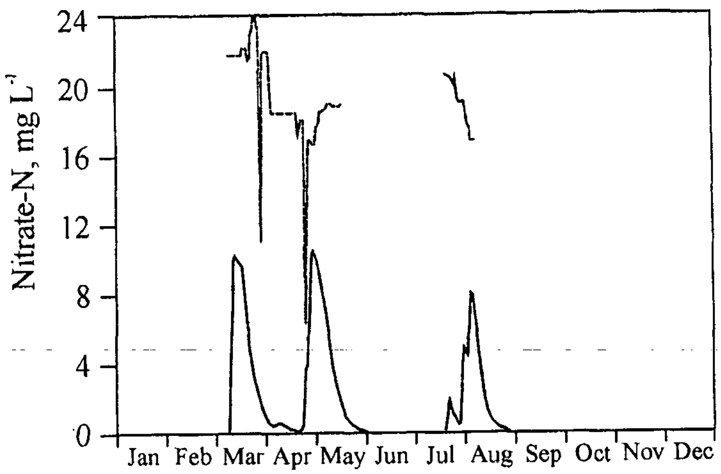

Fig. 3. Inlet (*top line*) and outlet (*bottom line*) nitrate N concentrations for a 1-ha wetland receiving tile drainage water from a 100-ha watershed (Crumpton and Baker, 1993).

sis, tile drain discharge can add large nitrate loads to surface waters, impairing their quality if not sufficiently diluted. Nitrogen balance sheets and delta-^{15}N data collected by Clay et al. (1997) in South Dakota suggest that denitrification may be significant in poorly drained soils, but is negligible if these soils are tile drained.

The potential for reducing the nitrate load of tile discharge water by routing it through a wetland was investigated in Iowa by Crumpton and Baker (1993). From the data collected they developed a model to determine the size of wetland required to reduce tile inflow of a given nitrate concentration and volume to levels meeting drinking water standards. Their calculations show that tile discharges containing up to 24 mg nitrate N L^{-1} from a 100 ha drainage field can be cleaned up to less than 10 mg nitrate N L^{-1} by passing it through a 1 ha wetland (Fig. 3).

Studies were conducted on the potential for using subsurface drains as a means of controlling water table depth through drainage and subirrigation (Fausey et al., 1995). Results showed that nitrate concentrations in column leachates and quantity of nitrate leached were reduced as depth to water table decreased and time between fertilizer application and initiation of leaching treatments increased (Jiang et al., 1997). This suggests that such treatments may increase nitrate removal by denitrification. This conclusion agreed with results obtained by Jacinthe et al. (1999) who showed that nitrous oxide emissions were greater for water tables less than 50 cm deep compared with those for water tables more than 50 cm deep (Table 2), and that emissions increased with time for shallow water tables. In field plots, Fausey and Cooper (1995) showed that corn and soybean yield could be increased by maintaining the water table 10 to 50 cm below the soil surface during most of the growing season by using tile drains for subirrigation (Table 3).

Table 2. Cumulative amount of N_2O and N_2 emitted from the surface of the soil columns with a static water table (WTM1) and dynamic water table (WTM2) (Jacinthe and Dick, 1996).

Soil	Treatment†	Total N_2O emitted during period: Day 13–35	Day 91–116	Total amount emitted during experiment as: N_2O	N_2	$N_2O + N_2$ emitted as % initial N
		mg N column^{-1}				
Blount	WTM1	12 (1.3)‡	42 (34)	93 (39)	151 (96)	9 (4)§
	WTM2	125 (90)	59 (0.1)	251 (91)	373 (152)	24 (7)
Clermont	WTM1	22 (11)	90 (76)	189 (84)	174 (71)	14 (5)
	WTM2	164 (98)	40 (18)	311 (172)	765 (435)	43 (20)
Huntington	WTM1	24 (14)	80 (86)	192 (128)	89 (65)	9 (5)
	WTM2	297 (334)	130 (115)	565 (529)	329 (268)	29 (20)
Analysis of Variance						
Source		$P < F$				
Soil (S)		0.638	0.489	0.472	0.668	0.652
WTM (T)		0.054	0.883	0.131	0.030	0.039
S × T		0.688	0.512	0.685	0.698	0.859

† WTM1 = water table 50 cm below soil surface for first 92d, 10 cm thereafter. WTM2 = water table 50 cm below soil surface first 4d, increased to 10 cm by d8, decreased gradually to 70 cm by d44, increased to 50 cm by d50, then to 10 cm on d92.

‡ Value in parentheses is standard deviation.

§ Indigeneous NO_3–N present in Blount, Clermont and Huntington columns was 513, 414 and 1075 mg N column^{-1}, respectively. Initial N = (indigeneous N + added N).

Table 3. Effects of water table depth (controlled by tile drainage and subirrigation) on corn and soybean yields at Hoytville, Ohio (from Fausey and Cooper, 1995).

Water table depth	Corn yield	Water table at 25 cm	Soybean
cm	Mg ha^{-1}		Mg ha^{-1}
25	11.5	Full season (to 9/30)	4.8
50	11.3	Early season (to 8/15)	4.1
Free drainage	10.2	Free drainage	3.8

Nitrogen Fertilizer and Manure Management Practices

Research was conducted at almost all locations on improving the management of N fertilizers and manure used in crop production. These included studies to evaluate existing soil testing procedures, technologies to improve fertilizer application practices, and new technologies using various crop growth parameters as monitors to determine crop N sufficiency. This latter approach will be discussed in a separate section that follows.

Soil N Tests

On deep loess soils in western Iowa, cropped to continuous corn for 26 yr, Karlen et al. (1998a) found that about 50% of the fertilizer N applied at conventional rates could not be accounted for by crop removal. The PSNT and other soil nitrate testing indicated that there was a large accumulation of residual nitrate in these soils, suggesting that previous crops had been overfertilized. Stalk nitrate analysis supported this conclusion. Their results indicated that soil tests such as PSNT could be used to improve N fertilizer application rates. Nitrate moved through these deep loess soils at a rate of 0.5 to 1.0 m yr^{-1} and eventually showed up in base flow of streams fed by springs at the loess–till interface. In Wisconsin, Bundy and Andraski (1995) also found that both the PSNT and the PPNT were useful guides for determining proper N fertilizer rates. Kanwar et al. (1995) found that use of the PPNT soil test reduced nitrate losses in tile drainage, when compared with that for a standard 110 kg N ha^{-1} rate (Fig. 4).

From N rate response studies at 54 locations in Minnesota, Schmitt and Randall (1995) concluded that no fertilizer N should be applied to sites that have 19 or more mg nitrate N kg^{-1} soil at planting (PPNT). For Maryland, Steinhilber and Meisinger (1995) determined that little or no corn yield response could be expected for soils with a PSNT test of 22 or greater (Fig. 5). Data collected by Schepers et al. (1993) in the Platte River Valley of Nebraska showed that basing N fertilizer rates on the deep soil nitrate testing recommended in that state reduced ground water nitrate concentrations by about 0.5 mg L^{-1} yr^{-1} over a several-county area. Clay et al. (1995) in South Dakota concluded that soil samples collected for soil nitrate testing should be taken about 7.5 cm from the band for most representative results. There is ample evidence from MSEA research that the modern soil testing procedures currently recommended in many states do have potential to improve crop N

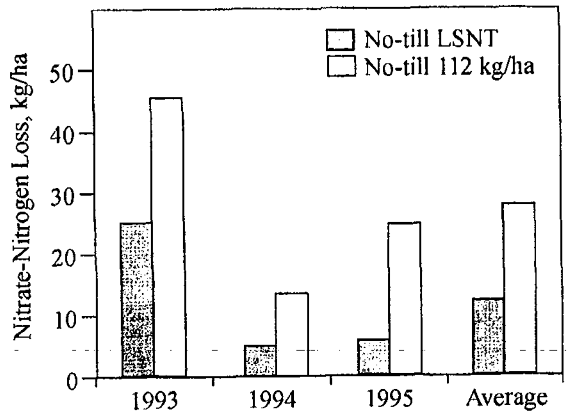

Fig. 4. Nitrate N lost through tile drainage for no-till plots fertilized according to Late Spring Nitrate Test (LSNT) compared with those receiving 112 kg N ha^{-1} (100 lb N acre^{-1}) annually (Kanwar et al., 1995).

management and thereby reduce nitrate leaching and water quality deterioration.

Fertilizer N Application

Effects of method of N fertilizer application were also investigated at several sites. At most locations it was demonstrated that N fertilizer applications were most effective and nitrate leaching was reduced by applying fertilizers in split application, with part added before planting and the remainder sidedressed later. Also, banding, compared with broadcast application, slowed the rate at which fertilizer N was nitrified, thereby reducing nitrate accumulations in the soil and subsequent nitrate leaching potential. Fertilizers also could be applied in the irrigation water (fertigation). Watts and Schepers (1995) found fertigation was practical with sprinkler irrigation, but cannot be recommended for furrow irrigation because water is not applied uniformly. MSEA scientists in Iowa (Ressler et al., 1997; Baker et al., 1997) showed that packing soil over a fertilizer band reduced water infiltration into the fertilizer band, slowing rate of nitrification and nitrate movement (Fig. 6). Lowery et al. (1995), working on sandy soils in Wisconsin, Iowa, and South Dakota, reduced nitrate leaching and improved N fertilizer use efficiency by banding fertilizer N on the shoulders of the ridges used in ridge-

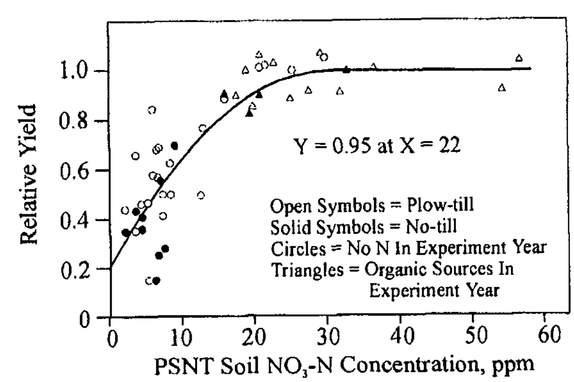

Fig. 5. Relation of corn relative yield to soil NO_3–N concentrations in the upper 30 cm of soil (Steinhibler and Meisinger, 1995).

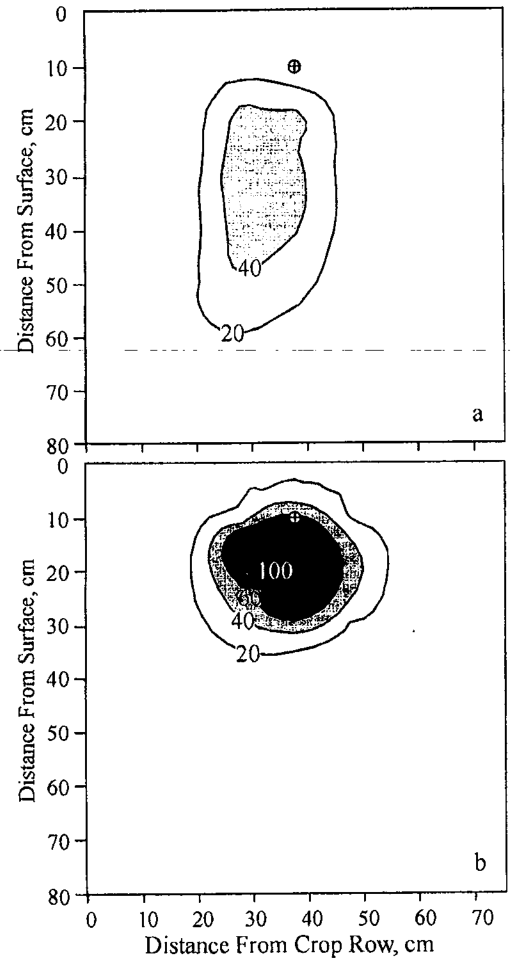

Fig. 6. Nitrate N concentrations 83 days after application: (*a*) conventional knife application; (*b*) soil compacted above fertilizer band. ⊕ Denotes location of fertilizer band. Units are kg ha^{-1} (Ressler et al., 1997).

till systems, compared with banding in furrows. Clay et al. (1994) showed that if open soil slots remained after banding anhydrous ammonia, leaching of nitrate during the next 85 d was much more rapid than when slots were closed. Doran et al. (1995) and Jacinthe and Dick (1997) determined that denitrification from well-drained corn fields was normally equivalent to only a few percent of the fertilizer N added to the crop.

Animal Manures

Effects of animal manures as a source of available crop N were investigated at only a few locations. However, at several locations longterm (more than 10 yr) residual effects of previous manure applications were observed, and several scientists concluded that previous manuring practices may have prolonged effects on N nutrition. Bundy and Andraski (1995) and Kanwar et al. (1995) concluded that use of the PPNT and PSNT soil tests should be recommended for manured soils. Francis et al. (1995) found that N in some manures, especially those with wide C/N ratios, are slow to mineralize during spring months, which may result in a temporary N deficiency during early crop growth. They concluded that use of N starter fertilizers would be desirable in such situations.

Table 4. Tillage and crop rotation effects on total NO_3–N loss in tile drainage water (Kanwar et al., 1998).

Year	Rain	Rotation†	Chisel plow	Moldboard plow	Ridge-till	No-till
	mm		NO_3–N loss with drainage water (kg ha^{-1})			
1990	1049	Cont. Corn	112a‡	64a	94a	120a
1991	973	Cont. Corn	85a	70a	70a	70a
1992	742	Cont. Corn	21a	21a	12a	22a
Average			73a	52a	61a	71a
1990	1049	Corn–Soy	60a	42a	34a	41a
1991	973	Corn–Soy	41a	40a	33a	34a
1992	742	Corn–Soy	19a	11a	13a	6a
Average			40a	31a	26a	25a
1990	1049	Soy–Corn	58a	46a	38a	41a
1991	973	Soy–Corn	51a	47a	36a	37a
1992	742	Soy–Corn	9a	13a	11a	6a
Average			39a	35a	28a	27a

† Cont. Corn = Continuous corn; Corn–Soy = Soybean after corn; Soy–Corn = Corn after soybean.
‡ Values followed by the same letters in the rows are not statistically different.

Impacts of Cropping Systems, Tillage, and Other Production Practices

Scientists have long known that certain cropping systems, tillage practices, and other production practices can have major effects on the availability and uptake of N by a crop. The MSEA research results added to this bank of knowledge and identified practices and situations where these choices greatly influenced nitrate leaching.

Cropping System Effects

At most locations the effects of continuous corn versus a corn–soybean rotation on crop production and water quality were investigated. When proper N credits were given for the soybean crop, nitrate leaching was usually less for the corn–soybean rotation than for continuous corn (Rice et al., 1995; Subler et al., 1995; Varvel et al., 1995; Albus and Knighton, 1998; Kanwar et al., 1997) (Table 4). There are several reasons for this. First, the soybean crop did not receive N fertilizer, and when credits were given for the soybean, amount of N fertilizer applied over two years was reduced well over 50% for the rotation compared with continuous corn. Second, soybeans are good scavengers for soil nitrate. They often leave less residual soil nitrate after harvest than continuous corn, again reducing nitrate leaching potential during fall and winter months. The relatively high N content of soybean residues and their rapid rate of decomposition may increase soil N availability for the following corn crop, further reducing fertilizer N requirement for corn (probably accounting for much of the N credit for soybeans). Omay et al. (1997) found that while the corn–soybean rotation had little effect on total N mineralized after 350 days of incubation, compared with continuous corn, the percent of total soil organic N mineralized was greater for soils in the rotation for a silt loam, but not for a loam. Thus, conclusions from all these

Table 5. Average yearly NO_3–N concentrations in subsurface drain water as a function of N management practice, tillage, and crop rotation for 1993 and 1994 (Kanwar et al., 1995).

Tillage	Rotation	N mgt. system	N application rate 1993	N application rate 1994	NO_3–N in corn plots 1993	NO_3–N in corn plots 1994	NO_3–N in soybean plots 1993	NO_3–N in soybean plots 1994
			kg ha^{-1}		mg L^{-1}			
NT	CS	LSNT	160	147	9.8	7.3	4.2	4.5
NT	CS	Single N	112	112	8.8	11.9	4.9	5.1
CP	CS	LSNT	103	167	11.1	9.7	4.6	7.0
CP	CS	Single N	112	112	8.9	11.2	8.4	6.1
CP	CS	Manure	84	237	11.6	13.2	4.8	7.0
CP	CC	Single N	134	134	11.6	14.0	–	–
CP	CC	Manure	82	280	11.1	18.6	–	–
CP	Strip C	N in corn strip	112	112	7.0	2.8	–	–
NT	Forage	No N app.	0	0	6.0	2.7	–	–

NT = No tillage; CP = Chisel plow; CS = Corn–soybean; CC = Continuous corn; LSNT = Late spring nitrogen test; Single N = Single application of N at planting time; Manure = Swine manure slurry injected in fall of previous year; Strip C = Strip cropping having strips of corn–soybeans–oats–berseem/clover; Forage = Three-year rotation of alfalfa.

studies indicate that nitrate leaching can be significantly reduced by rotating corn and soybeans compared with producing continuous corn if a proper N credit is given for the soybeans. Magnitude of these differences depends on soil and weather.

If insufficient N credits are given for the soybean crop, lysimeter studies (Klocke et al., 1999) showed that nitrate leaching with the corn–soybean rotation was significantly greater than for continuous corn. Using tagged N fertilizer, Rice et al. (1995) found that 94% of the applied fertilizer N could be accounted for in the soil and crop for the corn–soybean rotation, compared with only 84% for continuous corn. Much of this difference may be accounted for by differences in soil N immobilization or losses of ammonia gases to the atmosphere during corn maturation (Francis et al., 1993).

At a few locations a rotation of corn with alfalfa (*Medicago sativa* L.) was investigated. The PSNT soil test accurately showed that normally no N needs to be applied to corn following alfalfa (Bundy and Andraski, 1995). Kanwar et al. (1995) measured their lowest nitrate concentration in tile drainage water for corn following alfalfa compared with other cropping systems and also concluded that the PSNT soil test was reliable for this situation. At the Nebraska MSEA site soil and water nitrate concentrations were greatly reduced by five years of alfalfa (Watts et al., 1997). Rotations that included wheat (*Triticum aestivum* L.) were investigated in Ohio and Missouri (Ward et al., 1994). In general, almost all cropping systems studied exhibited less nitrate leaching potential than that observed for continuous corn, but generally profitability was also reduced (Batte et al., 1998). Also, with rotations annual fertilizer N inputs into the production system were reduced.

Effects of Tillage Practices

At many MSEA sites the effects of tillage practices on nitrate leaching potential were investigated. Ridge-till was compared with conventional tillage (usually chisel plow) in many of these studies. No-till and other reduced tillage practices were also often included. The effects of tillage practices on nitrate leaching potential were often site specific. In Iowa, Kanwar et al. (1997) found little difference among tillage practices in regard to soil nitrate leaching potential for tile-drained soils (Table 5). On a sandy soil in North Dakota, Albus and Knighton (1998) measured less residual nitrate after soybeans in ridge-till than in mulch tillage soils, but no differences after corn. On clay-pan soils in Missouri no-till generally exhibited less nitrate leaching than other tillage methods (Hughes et al., 1995). Nitrate leaching in these clay-pan soils generally occurs only after heavy rains are received at times when the clay-pan is dry and has cracks up to several cm in width (Kitchen et al., 1997). No-till tends to reduce cracking and subsequent movement of nitrate-containing water through the clay-pan (Table 6). However, for the deep loess soils of western Iowa, reduced tillage methods, compared with plowing or disking, resulted in greater water infiltration and movement of nitrate into the vadose zone (Steinheimer et al., 1998). Where measured, tillage method generally had little overall effect on total quantity of nitrate mineralized during a growing season, but did affect the timing of the mineralization activity. Bare tillage resulted in much more rapid mineralization early in the season, whereas reduced and no-till systems exhibited greater mineralization during midsummer, when N uptake by the corn crop was greatest.

Monitoring Crop Greenness and Variability

Approaches to managing the availability of N for crops in the past have generally been based on anticipated crop yield as estimated near planting time. Suffi-

Table 6. Seasonal root-zone water nitrate N (NO_3–N) concentrations at the summit landscape position for MSEA farming system, Centralia, MO, 1993–1994† (Hughes et al., 1995).

Year	Farming system‡	Pre-planting	Post-planting	Mid-season	Physical maturity	Post-harvest fallow
		NO_3–N concentration range (mg L^{-1})				
1993 (Corn)	MT 190 CS	3.0–6.6	4.2–*42.7*	0.1–*19.8*	0.0–2.1	0.0–*19.2*
	NT 140 CS	2.7–5.9	2.0–*15.7*	0.8–6.5	0.7–0.8	0.0–5.1
	MT 118 CSW	0.6–8.7	0.0–8.2	0.4–6.3	0.6–7.7	0.1–5.4
1994 (Soybean)	MT 190 CS	6.0–8.2	3.0–*10.4*	2.7–8.1	4.0–*12.8*	*24.5–27.3*
	NT 151 CS	4.8–*10.2*	0.6–*11.0*	1.2–1.4	0.0–1.0	8.7–*20.0*
	NT 151 CSW	1.1–3.9	0.8–4.6	0.7–3.1	0.1–0.5	No water

† Italic values exceed the U.S. Environmental Protection Agency's maximum contaminant level for drinking water (10 mg L^{-1}).
‡ MT = Mulch tillage; Numbers are N fertilizer rate in kg N ha^{-1}; C,S,W = Corn, soybean, and wheat, respectively.

cient fertilizer N was then applied before or shortly after planting to insure that the predicted yield could be obtained, ideally basing the application rate on the amount of residual nitrate in the soil at that time (nitrate soil testing) and on anticipated rate of soil N mineralization during the growing season. If the crop yield prediction was accurate within 5 to 10%, and if fertilizer N had been applied based on the best soil tests for the region, often crop yields were near optimum and nitrate leaching potential was minimized. However, crop yield frequently varies at least twofold from year to year because of differences in weather patterns, insect or disease incidence, or other reasons (Lamb et al., 1997; Birrell et al., 1995). In years when harvested yields are greatly below yield goals, even when we use our best N management practices, large amounts of nitrate may accumulate in the soil and be subject to leaching during the noncrop period after corn harvest. Also, soils are seldom uniform throughout a field, so applying sufficient fertilizer N to assure high yields for more productive areas of the field often results in overfertilization of the less productive areas. This may lead to greater nitrate leaching, particularly in those areas of the field that are more susceptible to leaching.

To address this problem, several MSEA scientists used a different approach to determining crop N needs and how these needs vary over a field. They documented that plant greenness was closely related to plant chlorophyll content, plant total N content, and potential crop yield. Schepers et al. (1995) demonstrated that plant N sufficiency could be adequately quantified by use of a chlorophyll meter if greenness of the plant was referenced against greenness measurements of a well-fertilized plant (Table 7). These observations were verified by Dystra et al. (1995) in South Dakota. Before the 6- to 8-leaf stage, significant plant N deficiencies reduced crop yield potential (probably by reducing the number of kernel primodoria formed), so permanent yield loss occurred. However, plant N deficiencies could be corrected by N fertilization after the 8-leaf stage of growth if N sufficiency did not fall below about 95% that of the well-fertilized reference plant (Varvel et al., 1997a). These results were obtained where N deficiency was the only factor limiting crop yield. These findings opened the door to a new approach for managing N fertilization of crops. By monitoring crop greenness relative to that of a well-fertilized crop strip through the field, followed by sidedressing or fertigating (applying fertilizer in irrigation water), the crop could essentially be spoon-fed the N it needs. This process vastly reduces frequency

Table 7. Effect of N fertilizer rate on corn leaf N content, chlorophyll meter readings, and corn grain yield (Schepers et al., 1995). Values in parentheses are percent of maximum value.

N rate	Leaf N	Chlorophyll meter reading	Corn grain yield
kg ha^{-1}	mg g^{-1}		kg ha^{-1}
0	18.9 (0.52)	27.7 (0.48)	4 010 (0.34)
75	27.3 (0.75)	42.6 (0.74)	7 900 (0.67)
150	33.5 (0.93)	51.3 (0.90)	10 410 (0.88)
225	34.8 (0.96)	56.4 (0.98)	11 040 (0.93)
300	36.2 (1.00)	57.3 (1.00)	11 750 (1.00)

of large nitrate accumulations in soil profiles, thereby reducing opportunity for nitrate leaching to occur. Watts and Schepers (1995) successfully used this approach for fertilization of irrigated corn. Blackmer and Schepers (1995) obtained best correlation between plant greenness and final crop yield at the R4 to R5 stages of corn development (Ritchie et al., 1996). Varvel et al. (1997b) found that both the chlorophyll meter and end-of-season stalk nitrate analysis accurately predicted N sufficiency levels. However, on sandy soils in Minnesota, Lamb et al. (1995b) measured low correlations between chlorophyll meter readings taken 30 to 60 days before crop maturation and final grain yields, possibly because the low water-holding capacity of sandy soils permitted more nitrate leaching to occur, when compared with finer textured soils.

While the chlorophyll meter was useful in assessing crop N fertilizer needs in medium and fine-textured soils, it was not without problems. The major problem was crop growth variability within a field. This variability could be caused by a number of factors—variability in soil properties, soil water content, insect and disease problems, or other factors. In using the chlorophyll meter, it is essential that the status of nutrients other than N be approximately equal for both the measured area of the field and the reference strips to which the measured area is compared. With variable soil conditions within a field, this would require a number of reference areas, one on each soil condition. This often is not practical. For example, Sudduth et al. (1995) found that productivity of clay-pan soils in Missouri is closely related to depth to clay-pan. Thus, reference strips would be needed for each change in soil depth.

For these reasons and because of other factors that affect crop greenness, MSEA scientists investigated the possibility of remotely sensing crop greenness. This approach allows the producer the option of using a GPS to differentially apply N fertilizer to those areas of the field that are in need. Three methods of remote sensing were investigated—use of aerial photographs, mounting economical crop greenness sensors (550 nm wavelength) on sidedressing or sprinkler irrigation equipment as it moves through the field, and use of satellite imagery. Several technical problems clearly indicated that use of satellite imagery was not yet a viable option (clouds, time delays in receiving images, cost).

Blackmer et al. (1994) determined that light reflectance from the corn canopy at 550 or at 710 nm could be used to assess crop greenness. In another investigation, Blackmer et al. (1996) showed that areas of a corn field needing N fertilizer could be assessed from inexpensive black-and-white photographs taken with a 536 nm filter (Fig. 7). However, Schepers et al. (1996) found that these relationships were less useful for water-stressed crops. On sandy soils in Minnesota, Tomer et al. (1997) also concluded that aerial infrared photographs could be used to monitor crop growth and N nutrition. Senay et al. (1998) demonstrated in Ohio that aerial multispectral band imagery was useful in predicting corn grain yields. Thus, remotely sensing crop greenness with aerial photography appears to be a practical method of as-

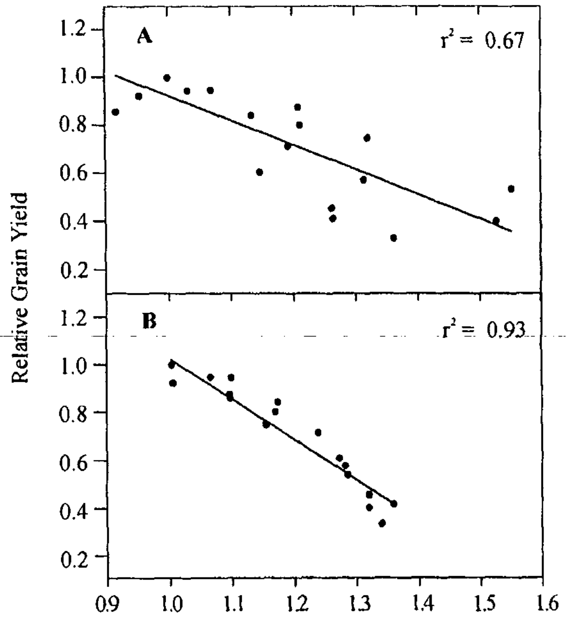

Fig. 7. Relationship between relative grain yield and relative digital counts for (*a*) raw data and (*b*) data corrected for vignetting, across four corn hybrids and five N rates (Blackmer et al., 1996).

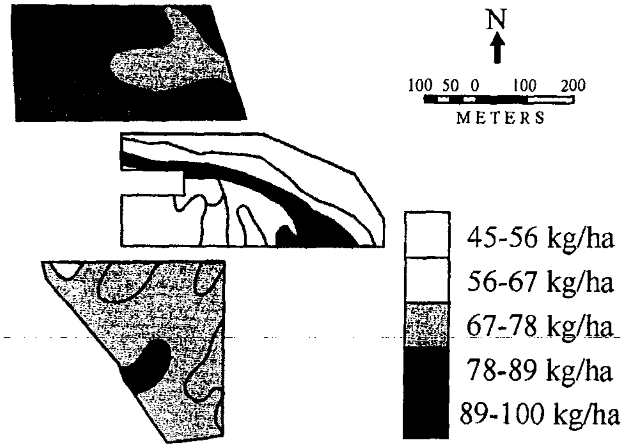

Fig. 8. Annual nitrate N leaching estimated from CREAMS for three adjacent fields in Ohio. Lines represent soil type boundaries (Wu et al., 1996).

sessing N sufficiency of the crop over the entire field. By use of GPS, those areas of the field needing additional N could then be sidedressed or fertigated. For this approach to be useful, however, it must be ascertained that differences in crop greenness are caused by N deficiencies and not by other factors.

Blackmer et al. (1996) described an inexpensive photometric cell, with a peak light sensitivity at 550 nm, that could be mounted on field equipment to measure crop greenness. Such cells could be mounted on irrigation machines or on high-clearance sidedressing machines to assess crop N needs as the machines traverse the field. The signal from these cells could then be used to turn fertilizer application equipment on and off as the machine moved through various parts of the field.

The new knowledge attained from the studies cited in this section opens up a new approach for N management for crop production—using the crop as a monitor of its N needs. It also provides a practical framework upon which to develop site-specific or precision farming systems. By using crop greenness as a monitor, it should be possible to control soil nitrate level at a sufficient but not excessive level in all parts of the field, thereby greatly reducing opportunity for nitrate leaching. Clay et al. (1997) showed that relative amounts of N mineralized and denitrified in a 65 ha field varied greatly from site to site, primarily depending on soil drainage. Kitchen et al. (1995) concluded that the variable rate approach holds much promise for use on the clay-pan soils of Missouri. However, for the sand plains in Minnesota, Lamb et al. (1995a) indicate that variable rate technology may be less useful because of difficulty in relating yield variability to soil properties and climate. One problem with this approach is that sometimes in the Midwest prolonged rainy periods may prevail during midsummer, limiting the time available for sidedressing. Thus, much more research and development are needed to bring these technologies to acceptable levels of application. At many MSEA locations research on the next steps in developing precision farming methods is underway.

Evaluation of Computer Simulation Models from MSEA Data

A number of factors influence soil N transformations and water movement through soils. Because of the complexity of these processes, coupled with the multitude of soil types and cultural practices involved in crop production, the potential combinations and interactions of all factors affecting N transformations and water movement are almost limitless. Therefore, realistic computer simulation models are desirable to determine the best combination of practices to use for any given situation. A number of such models have been developed in recent years. At several MSEA locations some of these models were evaluated in regard to their ability to assess crop yield, water movement, and nitrate leaching, using field data collected from MSEA experiments as a reference.

In Ohio, Wu et al. (1996) found that the model Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) provided reasonably accurate predictions of nitrate leaching through soil columns. They subdivided three 10-ha fields into 34 different hydrological environments, and using MSEA field data on hydrology and nitrate loading, estimated nitrate leaching losses from each of these units. Results showed that there was large variation in estimated leaching losses both among and within fields (Fig. 8). Annual nitrate leaching losses up to 120 kg N ha^{-1} were estimated. Neiber et al. (1995) applied the GLEAMS model to data collected from the sand plains in Minnesota and found the model useful, within limits, in helping to identify combinations of best management practices that minimize nitrate leaching and maintain crop yields.

Also in Ohio, Landa et al. (1999) estimated crop growth and nitrate movement and losses using the Root Zone Water Quality Model (RZWQM) using Ohio MSEA data. In most instances model assessments of crop growth and yield were fairly satisfactory. Assessments of residual soil nitrate after corn harvest were also reasonably accurate, but residual nitrate following soybeans was underpredicted, probably because soil water and N mineralization predictions were also in error. Also in Ohio, Nokes et al. (1996) used one year of MSEA field data to calibrate RZWQM, then applied the parameterized model to the next two years of field data. With this approach, the model reliably simulated data obtained on soil water content, nitrate in the root zone, corn growth, and yield. Using Missouri MSEA data, Ghidey et al. (1999) found that the RZWQM adequately predicted corn and soybean yields with minimum tillage, but overpredicted corn yield and underpredicted soybean yield with no-till. This model overpredicted runoff when these clay-pan soils were dry with large cracks. Karlen et al. (1998b) in Iowa found that the RZWQM adequately predicted effects of tillage practices on corn yields and N uptake, but the model was inadequate for predicting the fate of the fertilizer N applied, including leaching losses.

Using the Nitrate Leaching and Economic Analysis Package (NLEAP) on ground water quality data from northeast Colorado, Shaffer et al. (1995) accurately identified those areas in northeast Colorado that had relatively high nitrate concentrations in the ground water. This model appeared to be a very good tool for identifying potential hot spots for leaching. Follett (1995) calibrated NLEAP on a set of irrigated and nonirrigated plots on a sandy soil in North Dakota, then used the calibrated model to simulate nitrate movement for an identical set of plots. Variable N rates were applied. Predicted values were accurate and results showed that residual soil nitrate values in this soil were very sensitive to spring precipitation.

In Missouri, Heidenreich (1995) used the model Soil and Water Assessment Tool (SWAT) to study agricultural chemical movement from the 7250 ha watershed for Goodwater Creek. Subdividing the watershed into 73 virtual subbasins based on land use and soil characteristics, four yr of data were used to simulate nitrate movement. Only by adjusting parameters in the model could they obtain acceptable agreement between measured and simulated nitrate and yields. Tomer and Anderson (1995) developed a model for the sandy soils in Minnesota which described variation in soil water storage across a Sand Plain hillslope, which in turn appears to be related to crop yield potential for these soils. Both topography and presence of clay lenses in these sandy soils affected water storage.

The above are a few examples of the evaluation of the use of computer models in organizing and simulating data collected from the MSEA projects. It appears from these results that several of these models, with proper calibration and modifications, can frequently be used to assess the consequences of various agricultural practices on many soils, especially the effects of these practices on crop yield and nitrate leaching. In many instances, however, information upon which to base the calibration and modification procedures may be lacking, reducing the utility of some of these models. Also, it is apparent that none of the models is capable of accurate simulations in all situations at all times. Thus, it appears that existing models are useful tools for general planning of management practices, but failure rate is sufficiently frequent to limit their universal or site-specific use. Output from most models was less accurate as size of the target area evaluated decreased. Use of MSEA data with existing models demonstrated that in some instances these models gave grossly erroneous results. Unfortunately, there is frequently no convenient method by which we can evaluate the accuracy of the output of these models. Thus, at their present stages of development, it is extremely hazardous to base management or regulatory decisions on such model output. As we gain more knowledge from further research, the prediction capability of many of these models will likely improve and new models will be developed.

SUMMARY

The MSEA project was a comprehensive multistate multiagency research and education effort designed to improve our knowledge of factors causing agricultural pollution of our water resources and to lead us to practical new technologies by which such pollution can be reduced. The MSEA project was successful in achieving these goals. In many instances MSEA results identified and verified practices reported earlier to be beneficial in maintaining water quality. As examples, MSEA results showed that the recently developed soil nitrate tests used to guide N fertilization practices do greatly improve N management, resulting in maintenance of crop yields while reducing nitrate leaching, and often reducing fertilizer costs. MSEA results also verified the need to control water in order to control nitrate movement. Improved water and fertilizer management practices for irrigated agriculture were identified and evaluated. The effects of tile drainage on surface and ground water quality were measured, and practices (such as use of wetlands) that can be used to reduce the concentration of nitrates discharged by tile drains were studied. Improved N fertilizer management practices were identified, such as packing soil over a fertilizer band, applying water and fertilizer to alternate rows for furrow irrigation, and banding fertilizers on the shoulder of ridges used in ridge-till systems.

Probably the most significant result of the MSEA project was the recognition and initial development of practical technologies whereby N sufficiency for a crop can be determined by monitoring plant greenness. This finding has led to the development of remote sensing technologies to assess crop N sufficiency, followed by differential (site specific) application of fertilizer N to those areas of the field showing need. This research also strikingly demonstrated the variability that exists in crop growth and yield both within a field and between years. These MSEA results have led most locations into research to develop site specific or precision farming systems. Development and identification of limitations of computer simulation models were also provided by the MSEA research. This paper has summarized some of the achievements documented from the MSEA project and has identified instances in which this information is being used to improve water quality.

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